Control, Estimation, and Planning for Aerial Manipulation

Justin Thomas, Shaojie Shen, and Vijay Kumar

Penn
University of Pennsylvania

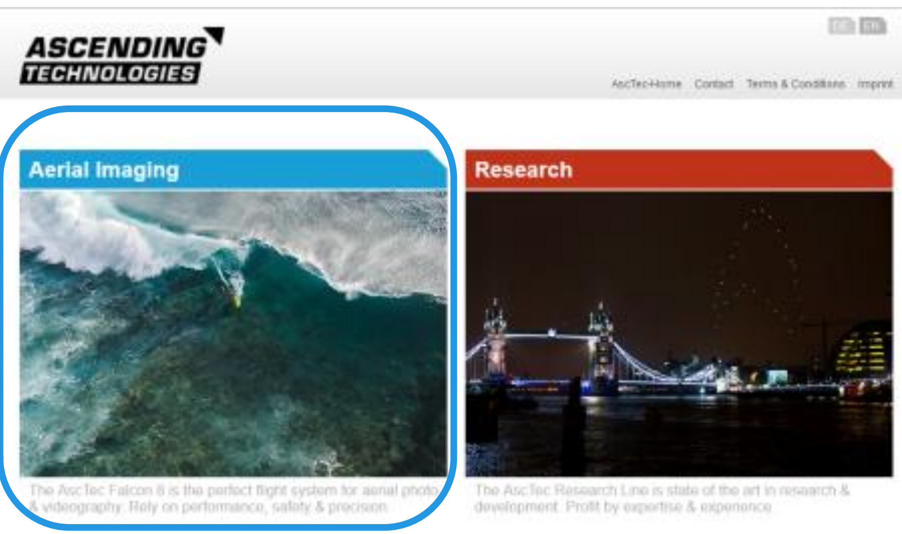
GRASP
Laboratory

Outline

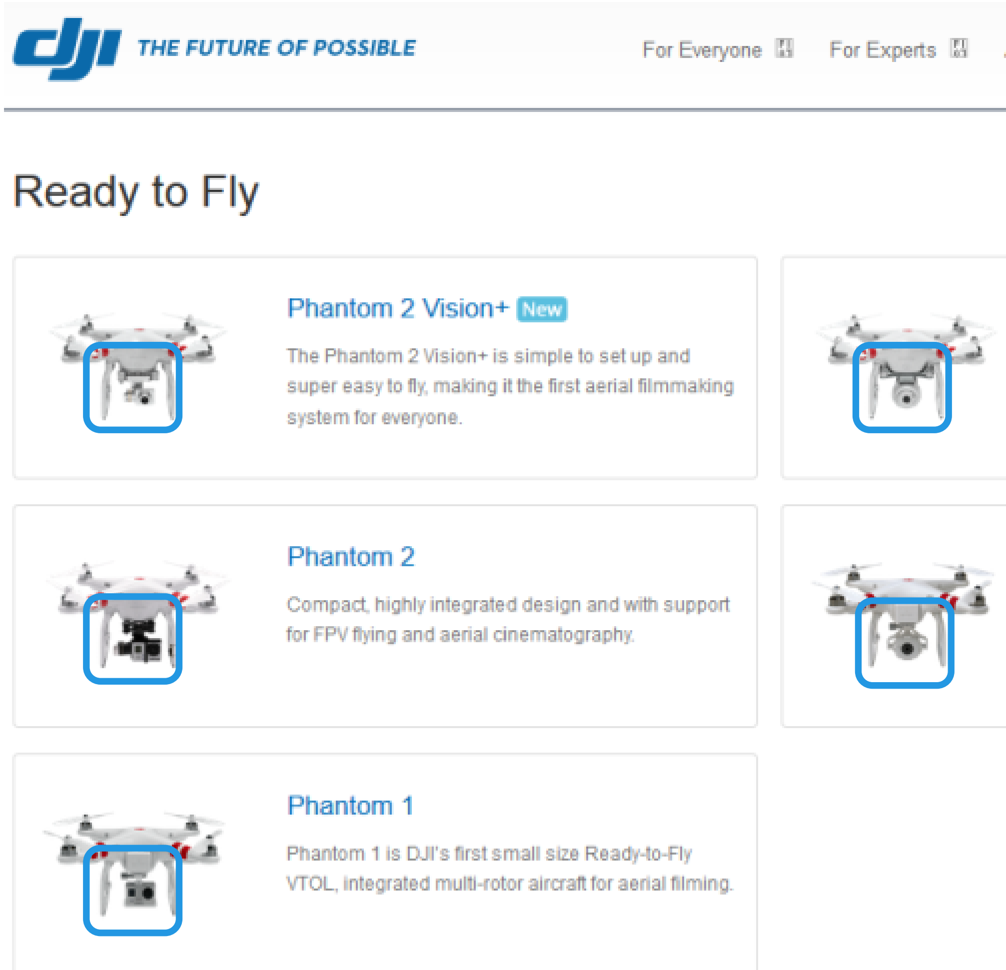
- Avian-Inspired Grasping
  - Planning
- Image Based Visual Servoing (IBVS) for Grasping
  - Planning & Control in the Image Space
- Cooperative Manipulation
- Suspended Payloads
  - Single robot
  - Multiple robots
- Vision Based Formations

Current Role of UAVs

- Look but don't touch



http://www.asctec.de



http://www.dji.com/products

Importance of Interaction

- Construction
- Perching
  - Save energy during persistent surveillance
  - Recharging
- Transportation of
  - Objects
  - Sensors
  - Other Robots

Penn

Our Interests

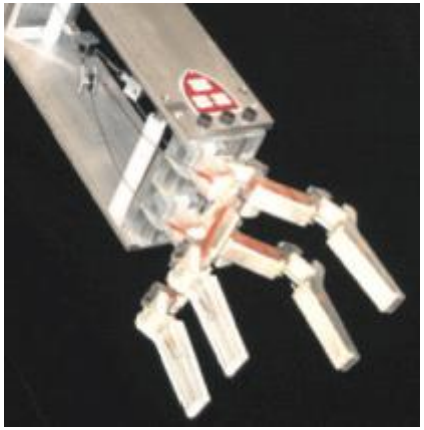
- Rapid acquisition of targets
- Ascribe high-speed, high-success grasping to quadrotors

Background

- Previous Grasping

Penetration-based Gripper on a UAV
[Mellinger et al, 2010]

1 DOF Actuated Gripper on a UAV
[Lindsey et al, 2011]



Adaptive SDM Hand
[Dollar et al, 2010]

Passive Perching
[Doyle et al, 2011]

Quasi-Static Examples

[Lindsey, Mellinger, and Kumar, 2012]

[Mellinger, Shomin, Michael, and Kumar, 2010]

Inspiration: A Red Kite

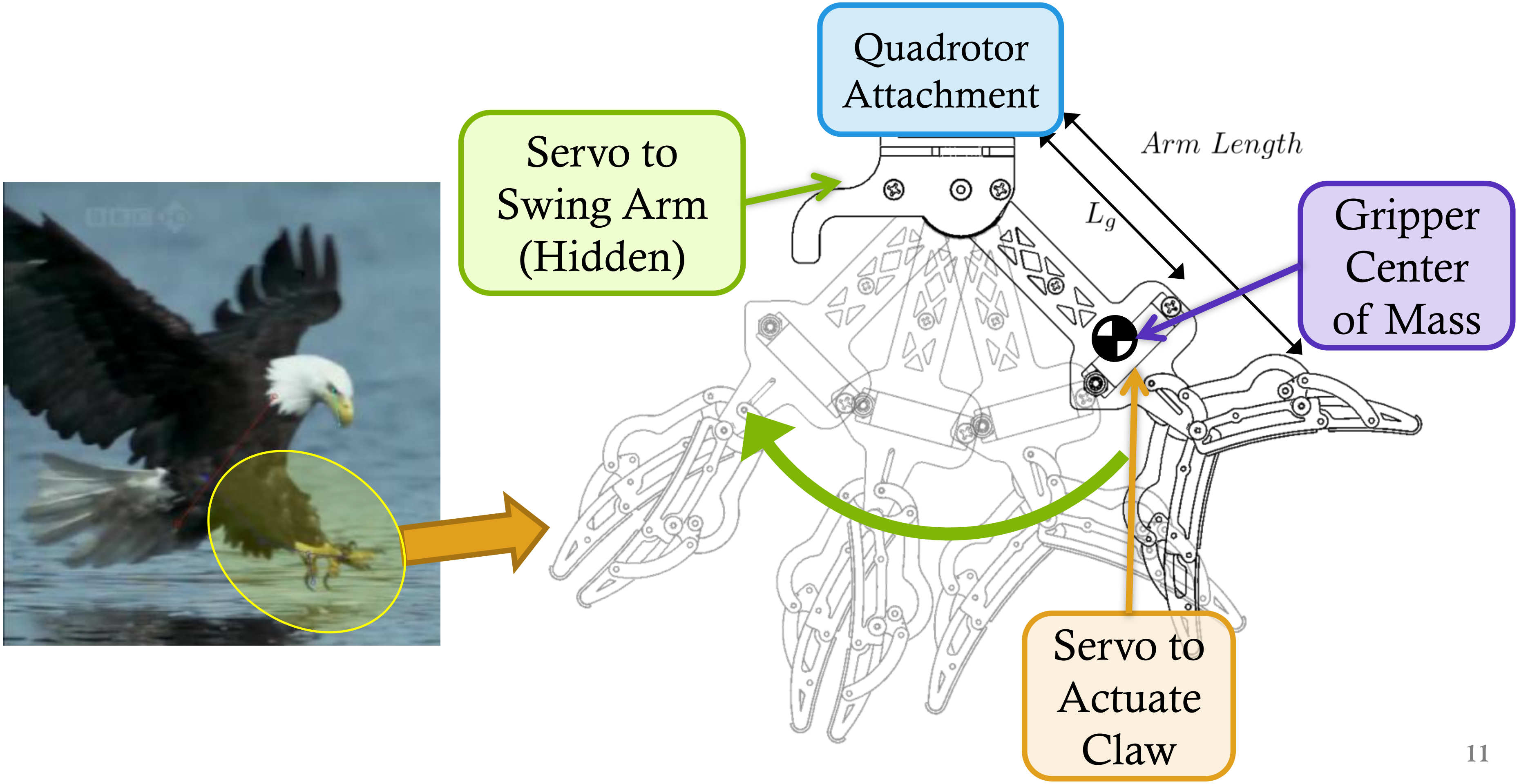
Inspiration: A Bald Eagle

A Bio-Inspired Appendage

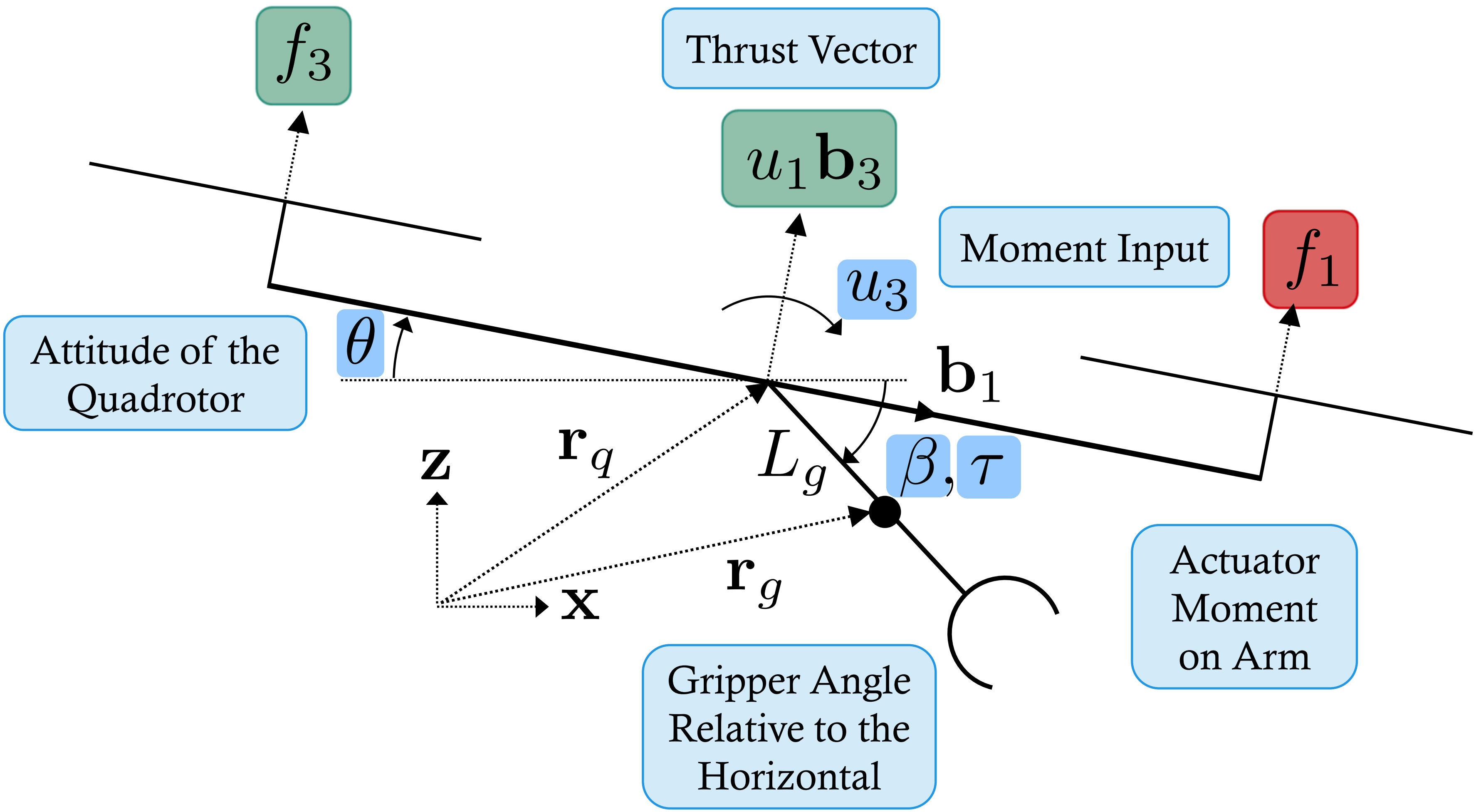
- Objectives
  - Reduce relative motion between claw and target
  - Independently actuate rotation and grasping
  - Grasp arbitrary shapes (wrap claws around target)
  - Ability to perch

A Bio-Inspired Appendage

- Two Actuators
  - Independent Control of Rotation and Grasping

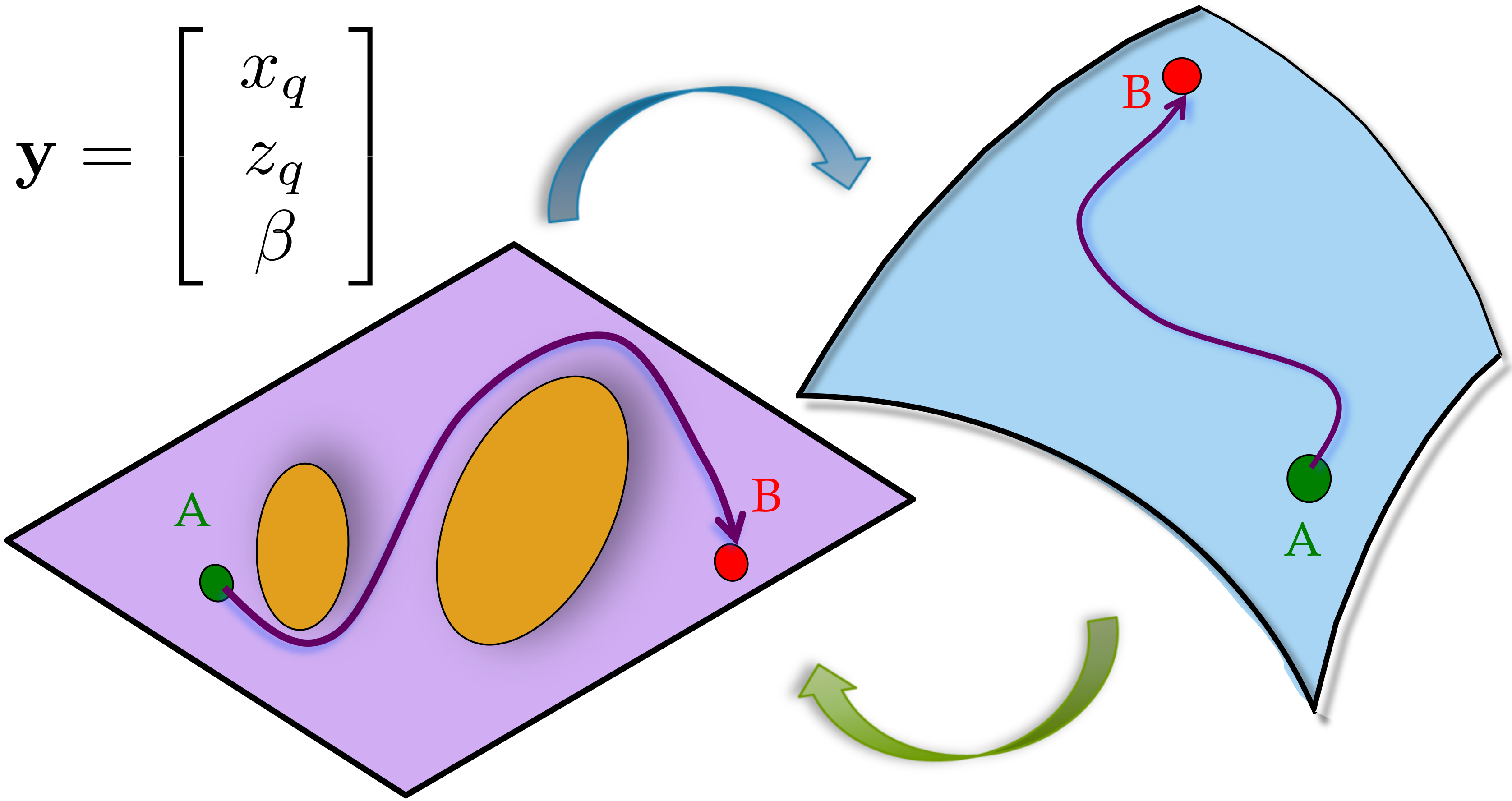


A Dynamic System



Differential Flatness

$$\mathbf{y} = \begin{bmatrix} x_q \\ z_q \\ \beta \end{bmatrix}$$



$$\begin{bmatrix} x_q \\ z_q \\ \theta \\ \beta \\ \dot{x}_q \\ \dot{z}_q \\ \dot{\theta} \\ \dot{\beta} \end{bmatrix}$$

Murray, R., Rathinam, M., and Sluis, W., 1995. "Differential flatness of mechanical control systems: A catalog of prototype systems". In ASME International Congress and Exposition, Citeseer.

Trajectory Generation

- The inputs of the system are the 4th derivatives of position and the angle, β
- Motivates minimum-snap trajectories

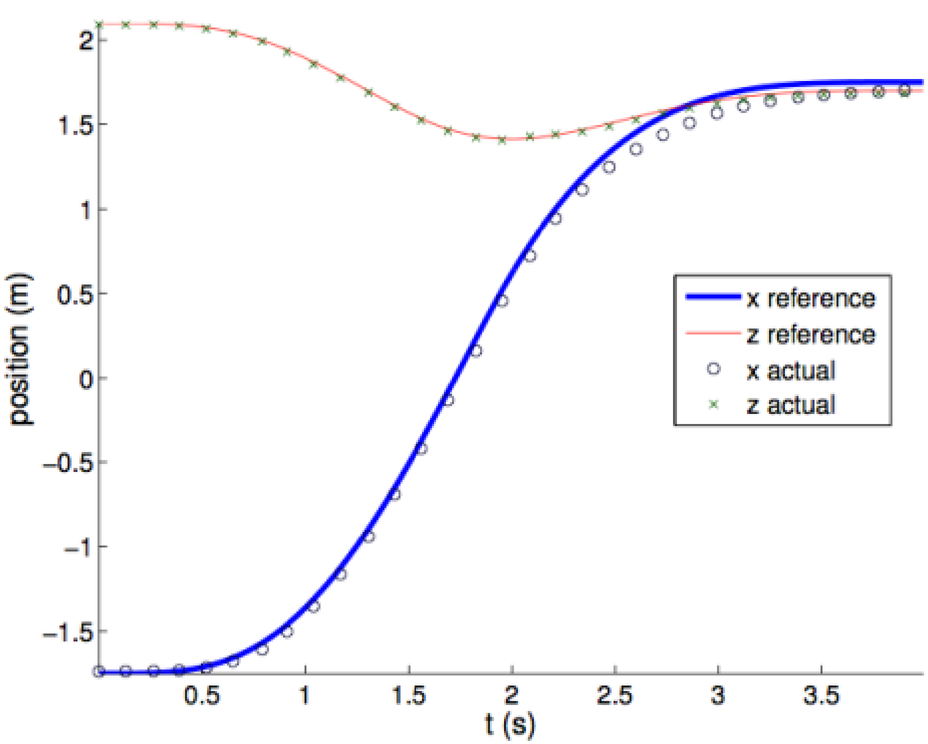
$$\mathcal{J}_i = \int_{t_0}^{t_f} \left\| y_i^{(4)}(t) \right\|^2 dt \quad \text{for} \quad i = 1, 2, 3$$

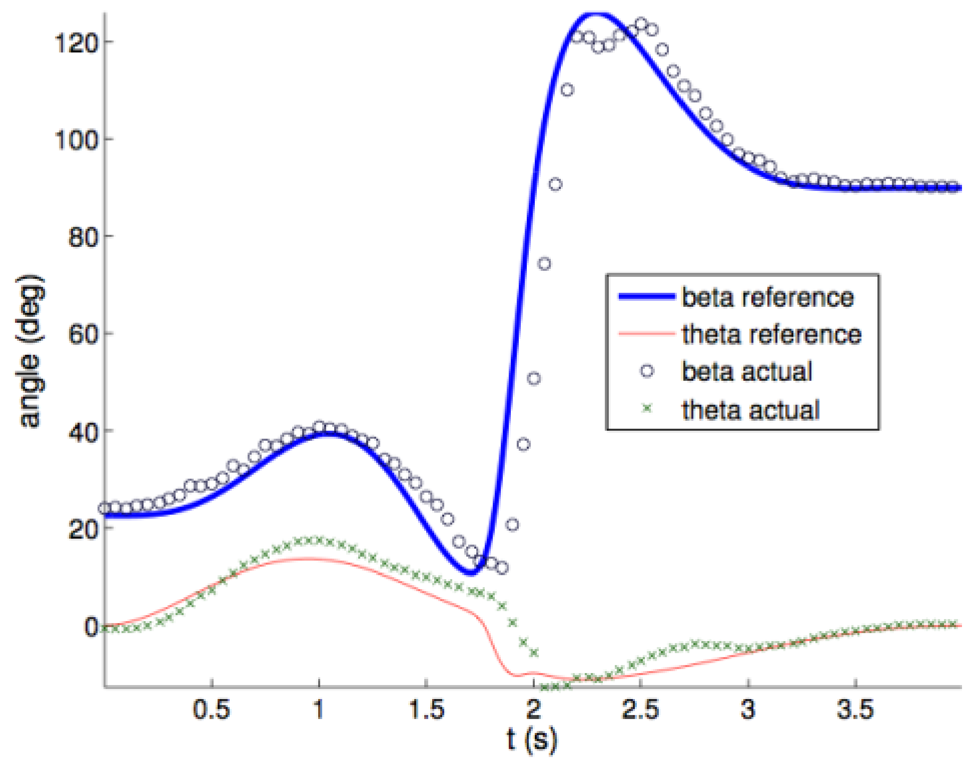
- Can be expressed as a quadratic program

Mellinger, D., and Kumar, V., 2011. "Minimum snap trajectory generation and control for quadrotors". In 2011 IEEE International Conference on Robotics and Automation, IEEE, pp. 2520–2525.

Trajectory Generation

- Trajectories and Experimental Results





Video

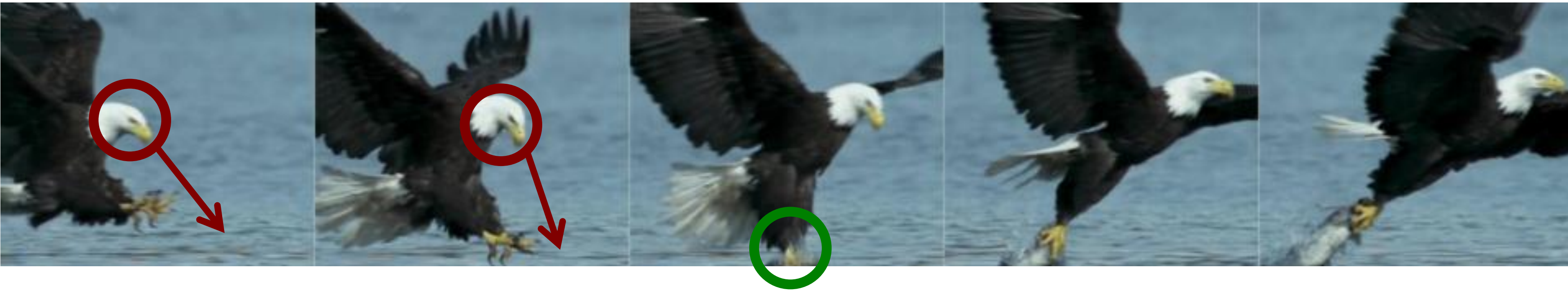
http://www.jtwebs.net/idetc-2013/

Conclusions & Limitations

- We have demonstrated Avian-Inspired, High-Speed, Dynamic Aerial Grasping
- Future Work:
  - Decrease inertia and weight of gripper
  - Differential flatness of the actuated gripper system in 3D
  - Eliminate dependence upon a motion capture system
    - Use Image-based visual servoing
    - Plan feasible trajectories directly in the image plane

Motivation for Vision

- Raptors use visual feedback



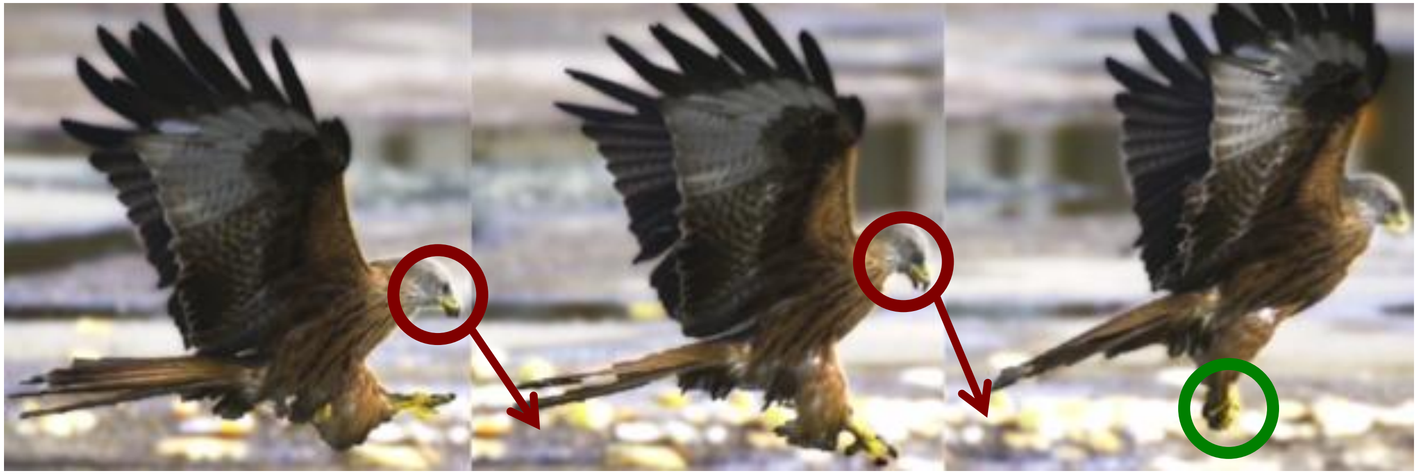


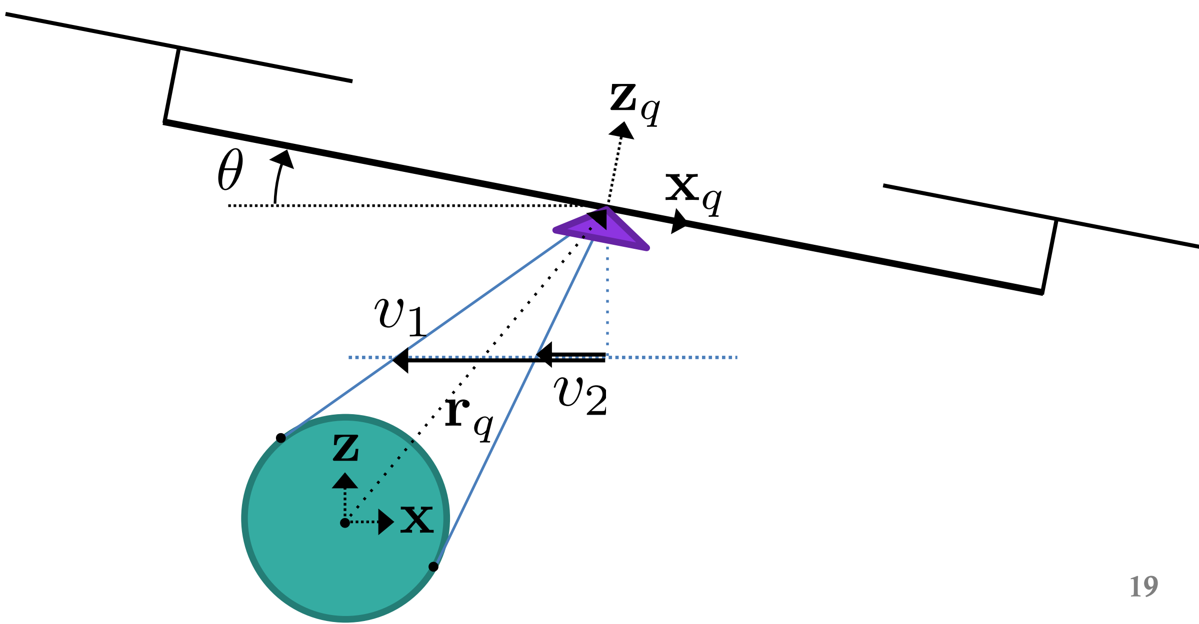
Image Features & Geometry

- Map the image features to a virtual "level" image plane and solve for image features

$$\mathbf{v} = \Gamma\left(\mathbf{r}_q\right)$$

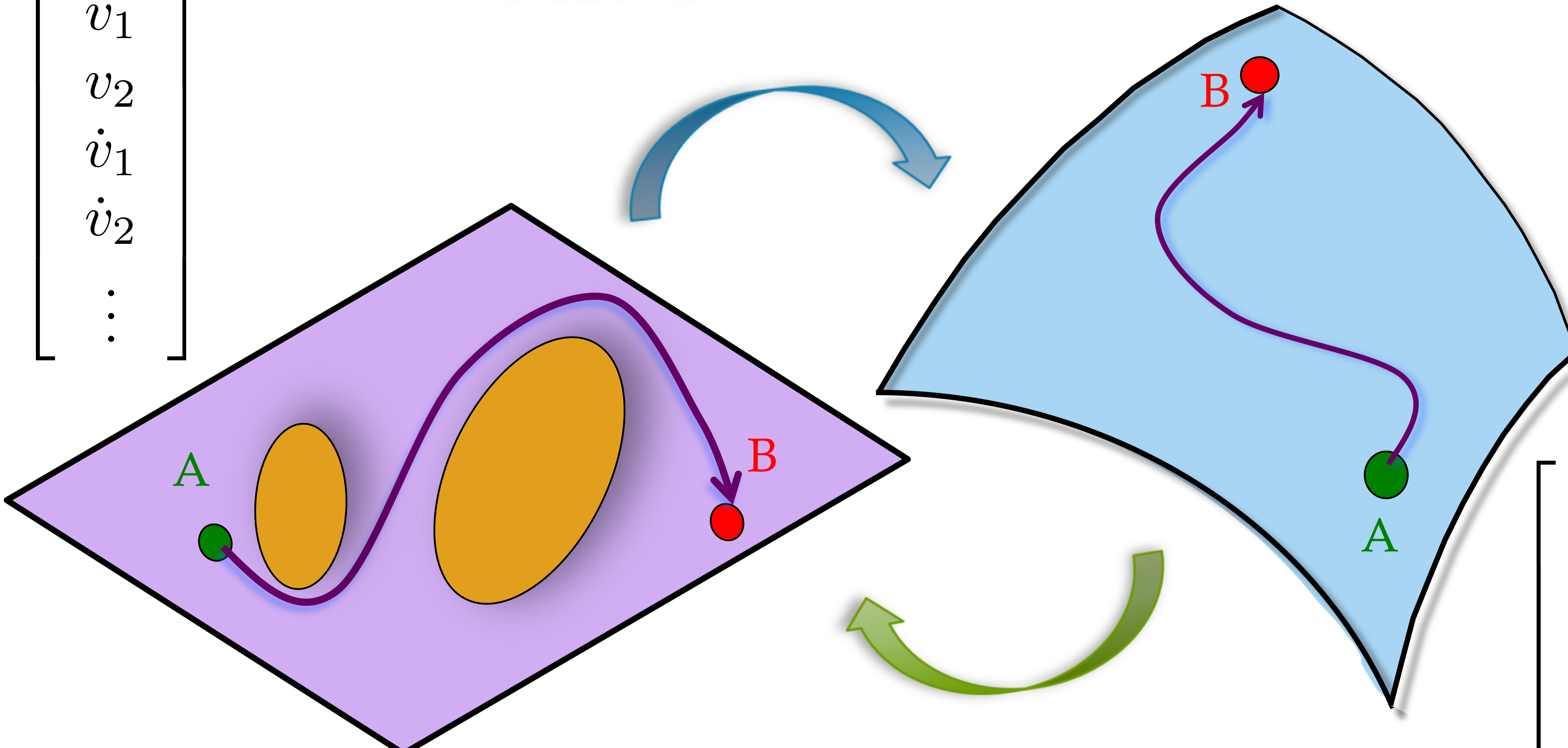
- Image Jacobian

$$\boxed{\dot{\mathbf{v}} = J\dot{\mathbf{r}}_q}$$



Planning: Differential Flatness

$$\begin{bmatrix} v_1 \\ v_2 \\ \dot{v}_1 \\ \dot{v}_2 \\ \vdots \end{bmatrix}$$



$$\begin{bmatrix} x_q \\ z_q \\ \theta \\ \dot{x}_q \\ \dot{z}_q \\ \dot{\theta} \end{bmatrix}$$

Minimum snap trajectory

$$\mathcal{J}_i = \int_{t_0}^{t_f} \left\| v_i^{(4)}(t) \right\|^2 dt$$

[similar to *Mellinger and Kumar*, 2011]

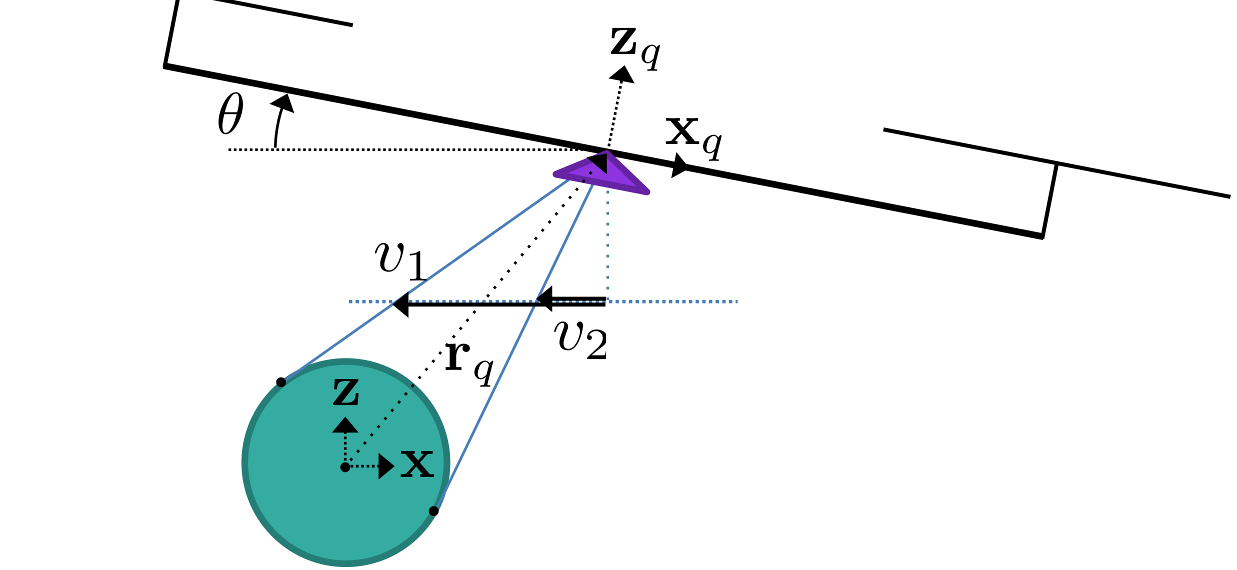
Attitude & Position Control

- SO(3) Attitude Controller [Lee, Leok, McClamroch, 2010]
- Position errors defined in the image feature space:

$$\mathbf{e}_v = \mathbf{v} - \mathbf{v}_d$$

- Desired thrust and attitude:

$$\mathbf{A} = \mathbf{G}_A + mJ^{-1}\left[-K_p\mathbf{e}_v - K_d\dot{\mathbf{e}}_v + \ddot{\mathbf{v}}_d\right]$$



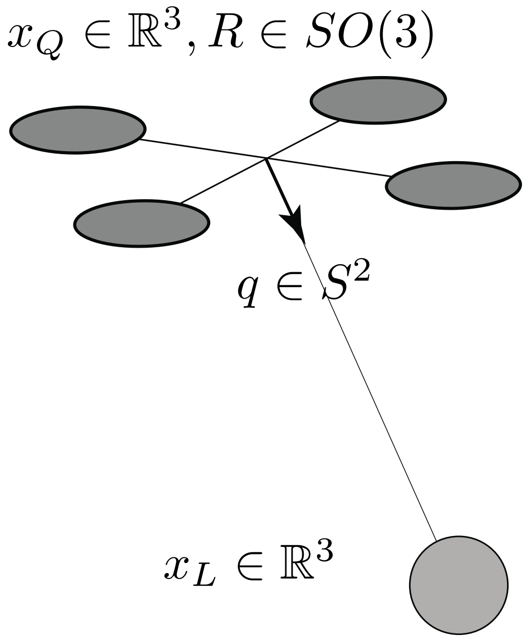
$$f = \mathbf{A} \cdot R\mathbf{e}_2$$

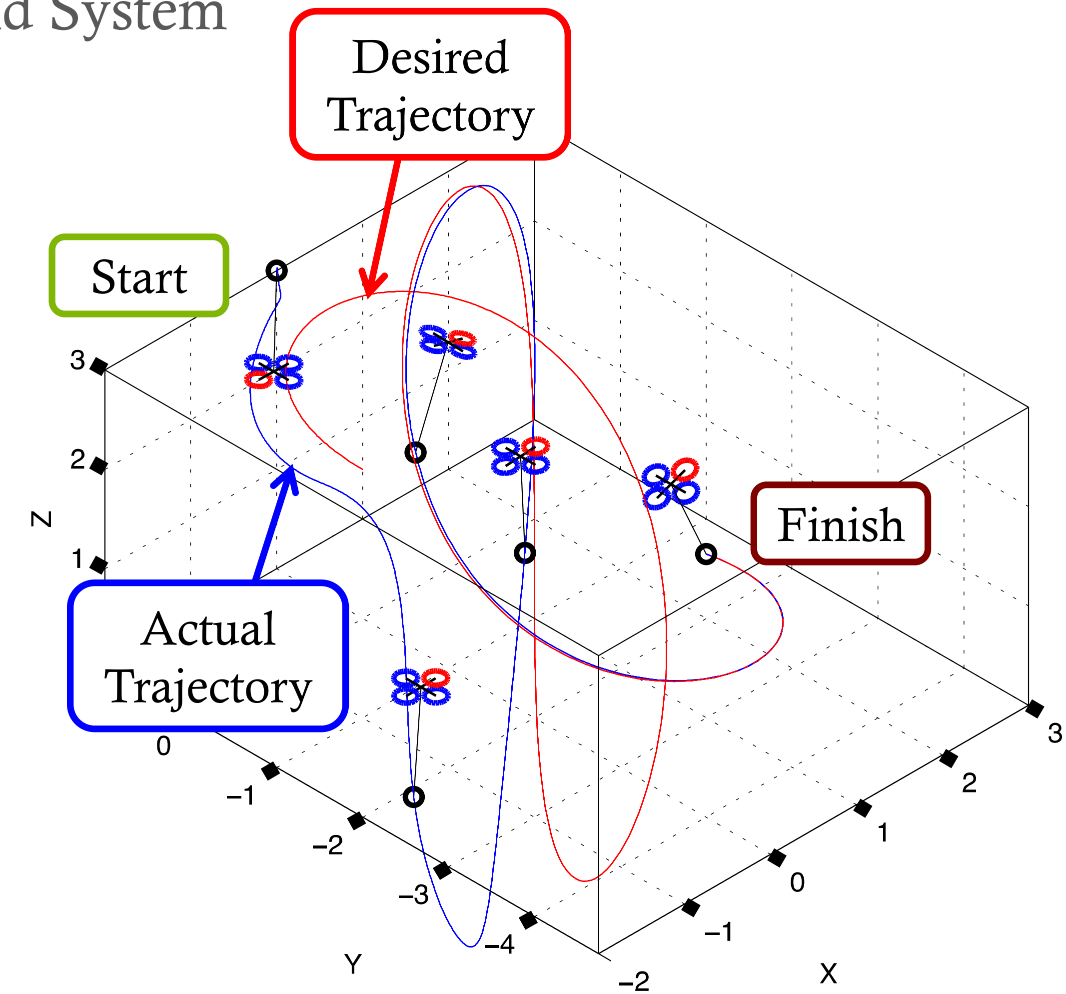
$$R_c\mathbf{e}_2 = \frac{\mathbf{A}}{\|\mathbf{A}\|}$$

Results

A Dynamic Slung Load

- Differentially-Flat Hybrid System
- Geometric Control Law

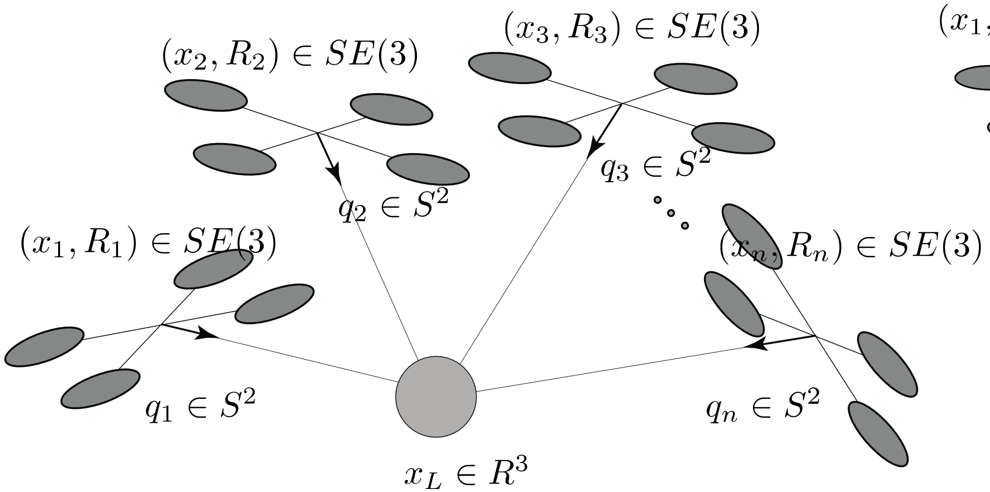


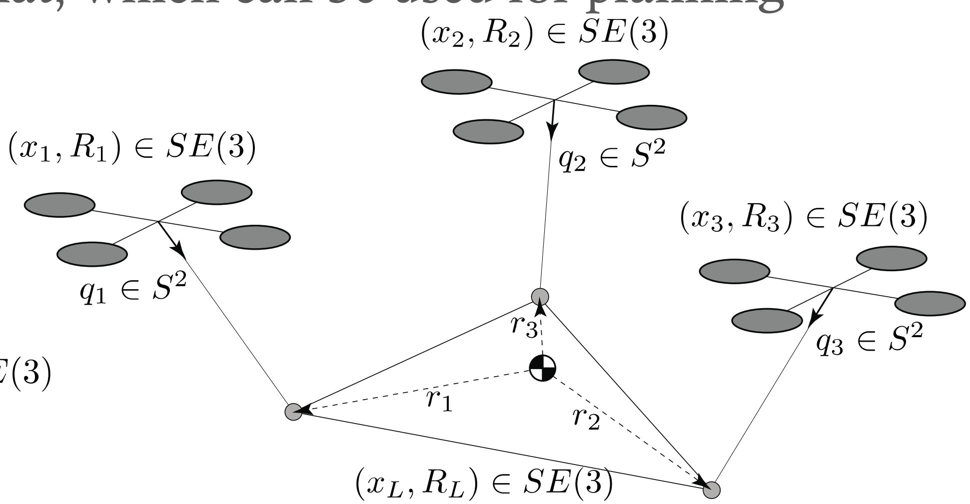


K. Sreenath, T. Lee, and V. Kumar, "Geometric control and differential flatness of a quadrotor UAV with a cable-suspended load," in 52nd IEEE Conference on Decision and Control, 2013, pp. 2269–2274.

Cooperative Transportation

- Previous approaches use quasi-static models and assume full actuation
- Our approach
  - Dynamic model of payload as a point load and as a rigid body
  - Both systems are differentially flat, which can be used for planning

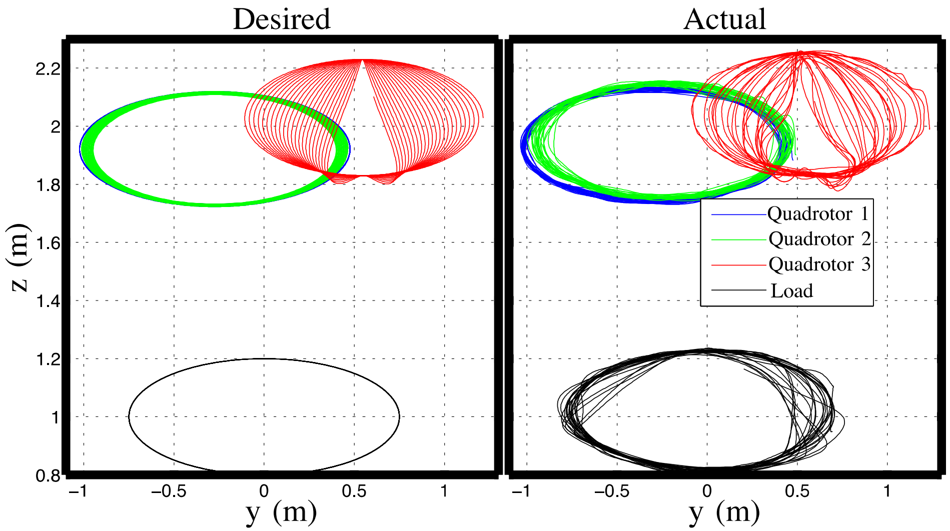




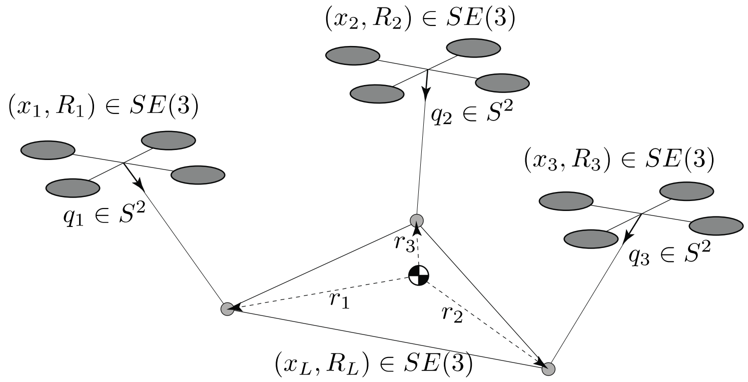
K. Sreenath and V. Kumar, "Dynamics, control and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotor robots, RSS Robotics Science and Systems, Berlin, Germany, June 2013. Best Paper Award

Cooperative Transportation

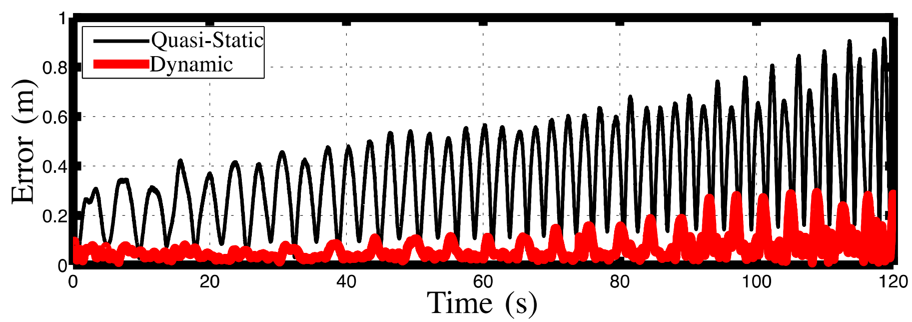
⌘ 3 quadrotors with a rigid body



Desired and Actual Trajectories performed by the Multiple Quadrotor with a rigid body payload



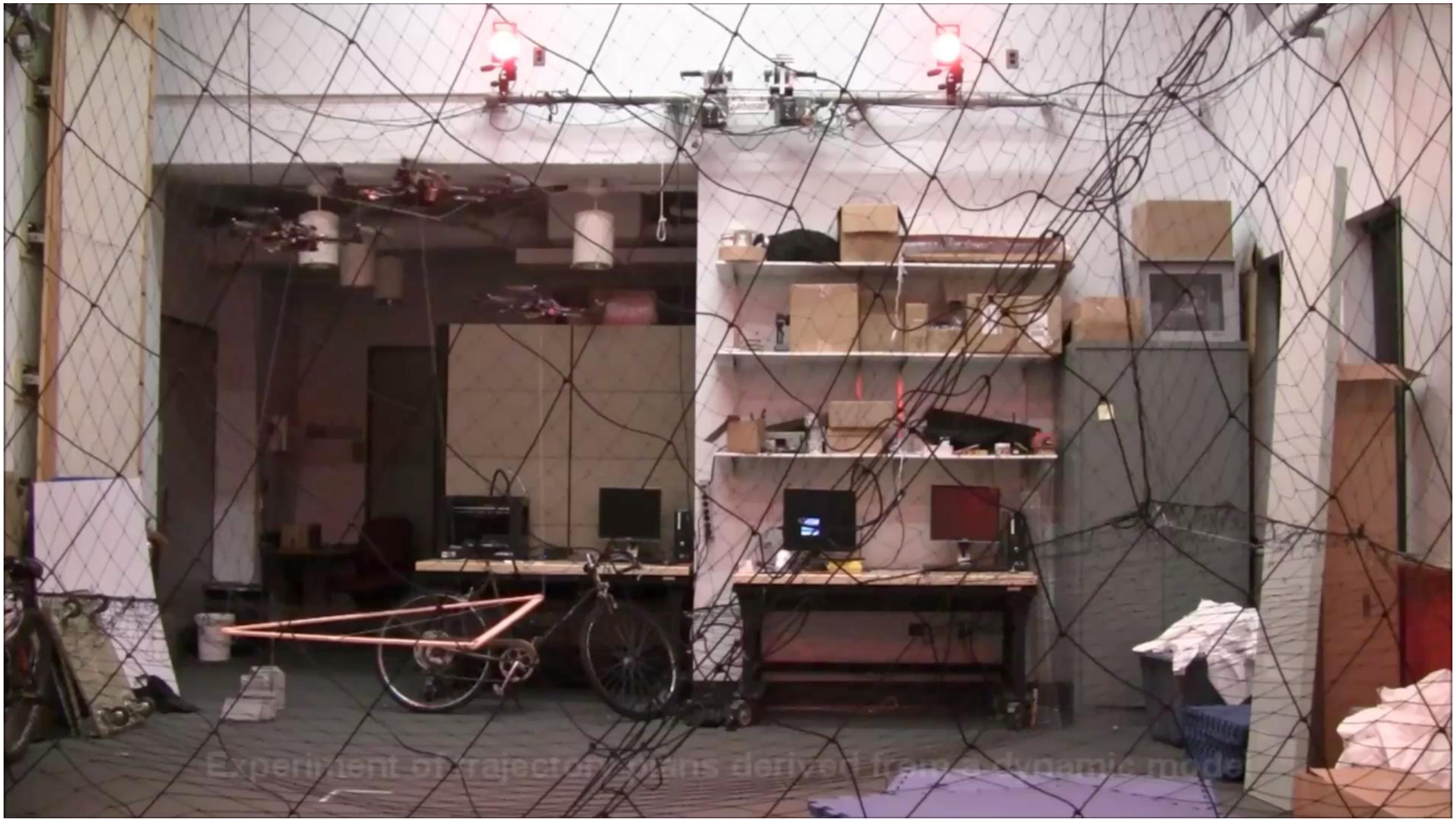
The 3 Quadrotors and the rigid payload



Comparison between Quasi Static and Dynamic Model

K. Sreenath and V. Kumar, "Dynamics, control and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotor robots, RSS Robotics Science and Systems, Berlin, Germany, June 2013. Best Paper Award

Cooperative Transportation



Vision-Based Formations

- Currently working on vision-based formation control
  - Bearing-based control laws
  - Gradient descent

How to Fly a MAV?

- Remote control
  - Requires line of sight and/or communication link
  - Requires skilled pilots
- Inertial navigation
  - Requires aviation grade IMU
  - Heavy and expensive
- GPS-based navigation
  - GPS is inaccurate
  - GPS can be unreliable

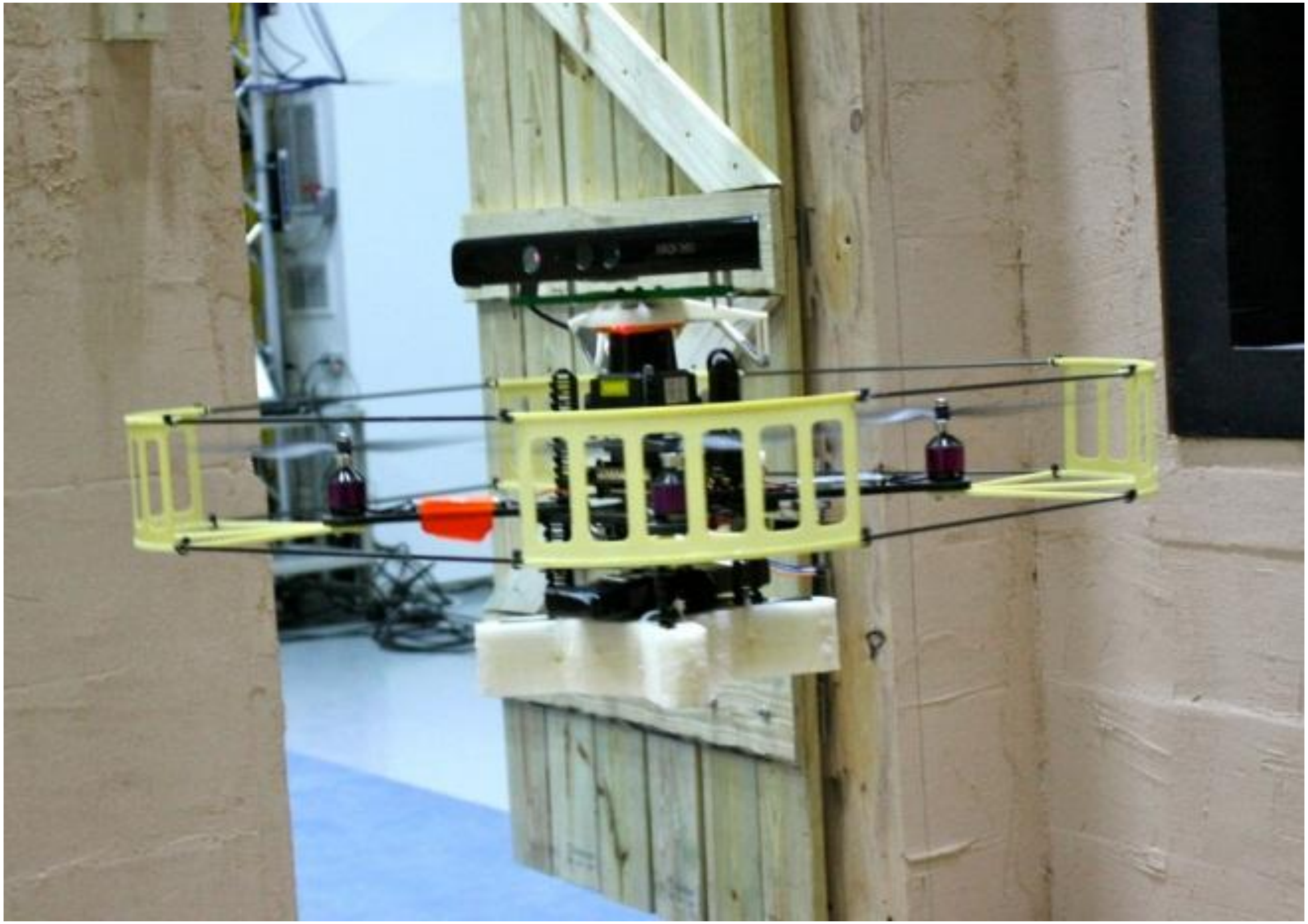
Challenges

- Fast vehicle dynamics (5th order system)
  - Requires real-time onboard processing
  - Requires accurate state estimates
- Limited payload (< 1kg)
  - Limited sensing
  - Limited computation

- Complex environments
  - Unknown environments
  - GPS unreliable or unavailable
- Intersection between estimation and control
  - Robustness
  - Low latency

Robot	Sensing	Computation	Mass	Environment	Year
	Laser IMU	Intel Atom 1.6GHz	1.7 kg	2.5D indoor	2010-2011
	Laser Kinect IMU	Intel Atom 1.6GHz	1.9 kg	2.5D indoor	2011-2012
	Cameras IMU	Intel Atom 1.6GHz	0.74 kg	3D indoor and limited outdoor	2012-2013
	Laser Cameras GPS IMU	Intel Core i3 1.8GHz	1.9 kg	3D indoor and outdoor	2013-2014
	Camera IMU	Intel Core i3 1.8GHz	1.3 kg	3D indoor and limited outdoor	2014

Laser-Based Autonomous Flight

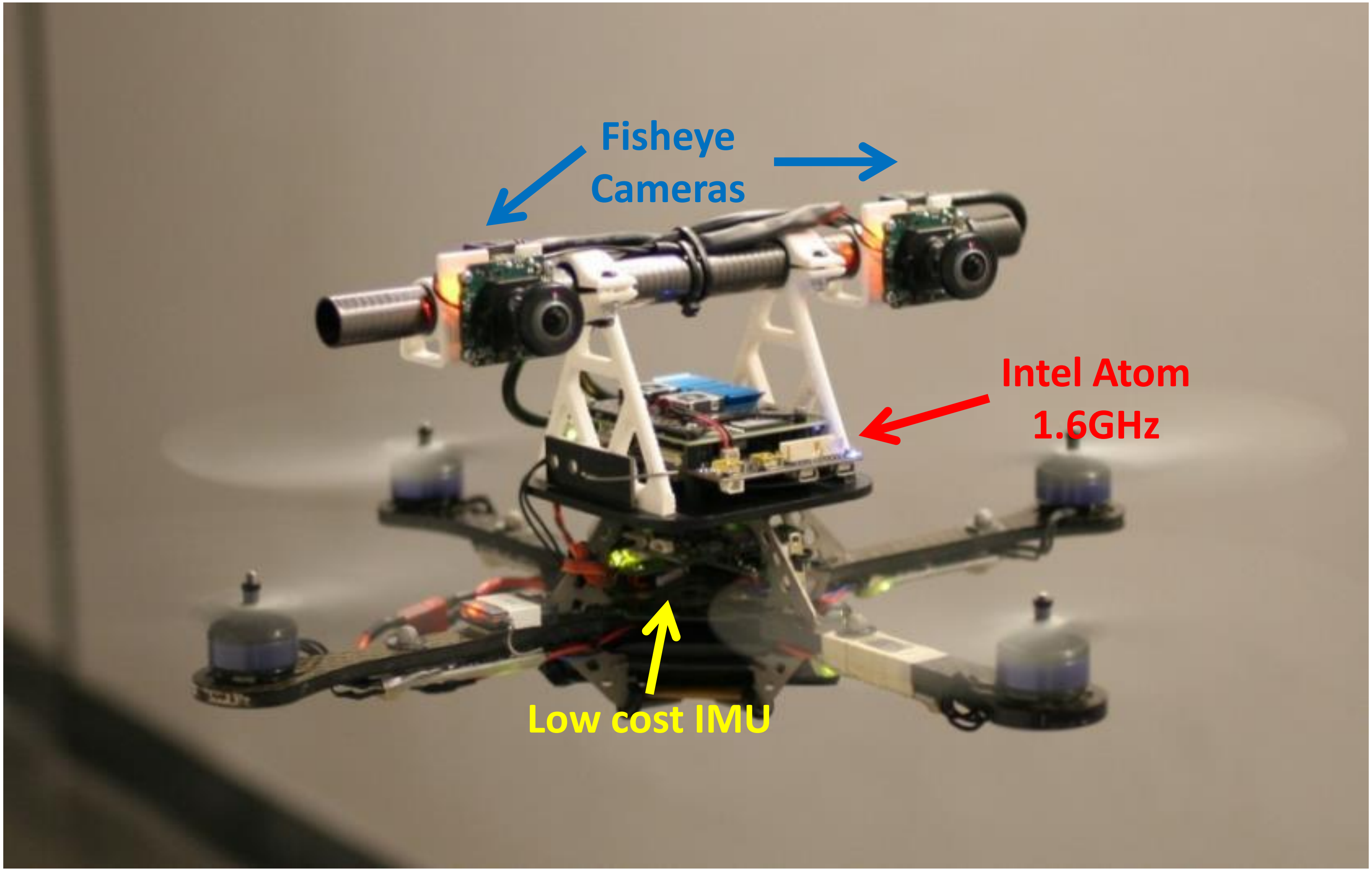


Autonomous Aerial Navigation
in Confined Indoor Environments

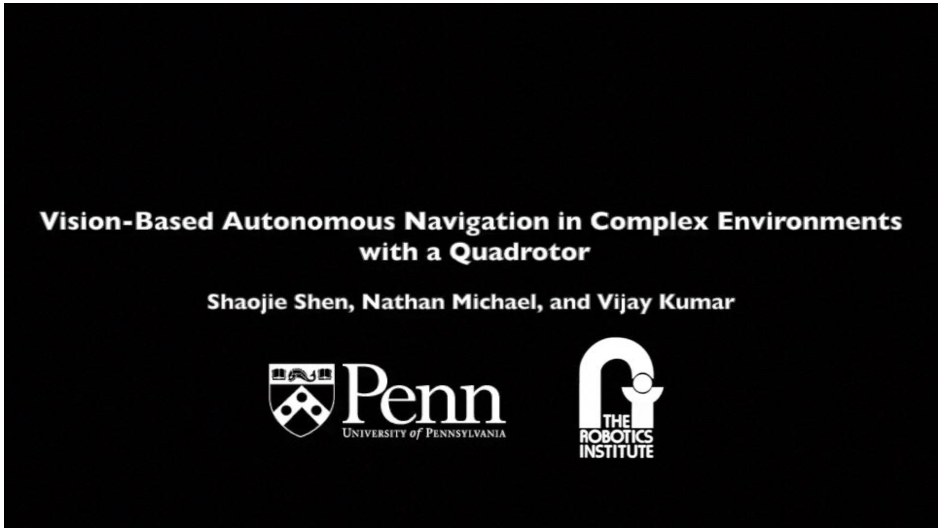
Shaojie Shen, Nathan Michael, Vijay Kumar

Penn
UNIVERSITY of PENNSYLVANIA

Vision-Based Autonomous Flight



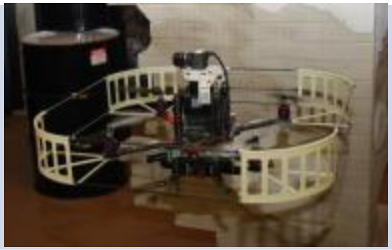
Indoor



Indoor and Outdoor SLAM

Robust State Estimation

- Power-on-and-go
  - Initialize from an arbitrary unknown state
- Autonomy
  - State estimation in a wide range of environments
- Fault-tolerant
  - Handle failure of one or more onboard sensors
- Fail-safe
  - Recover from total failure of all sensors

Robot	Sensing	Computation	Mass	Environment	Year
	Laser IMU	Intel Atom 1.6GHz	1.7 kg	2.5D indoor	2010-2011
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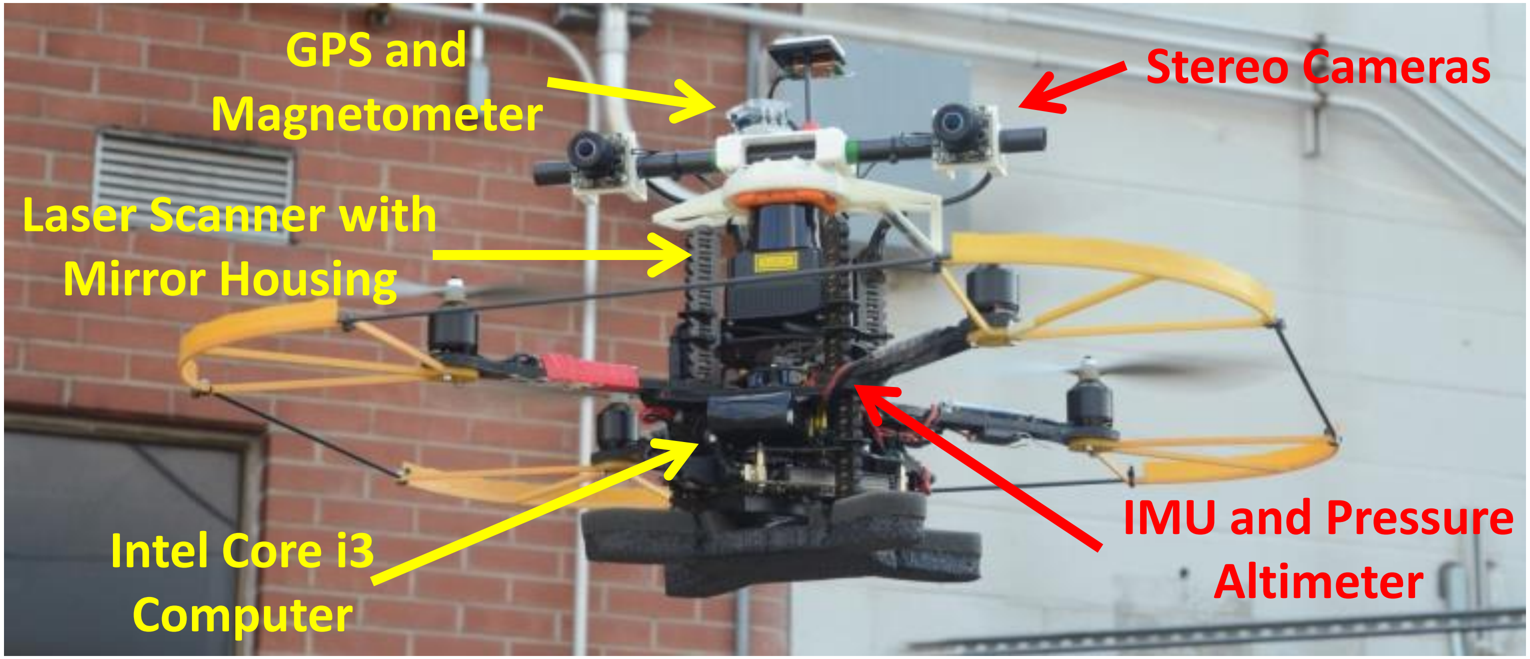
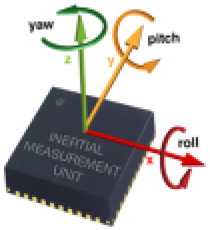
Robust Multi-Sensor Fusion for MAVs

- Contributions:
  - A modular Jacobian-free filter design for fusing heterogeneous sensors with minimum coding and calculation
  - Handling of GPS measurements to ensure smoothness
  - Extensive verification via field experiments

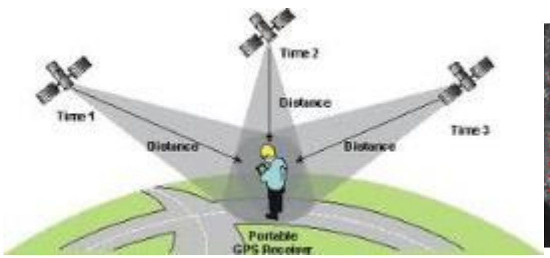


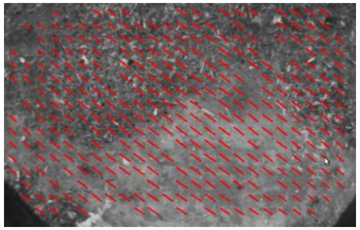
Heterogeneous Sensor Measurements

- Proprioceptive sensor
  - Low cost MEMS IMU

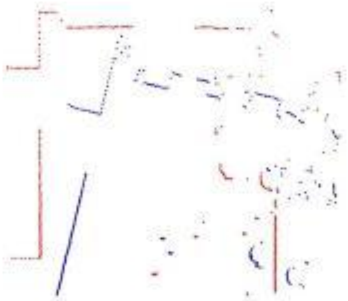


- Absolute measurements
  - GPS and Magmetometer
  - Pressure altimeter
  - Optical flow velocity sensor
  - $\mathbf{z}_t = h(\mathbf{x}_t) + \mathbf{n}_t$



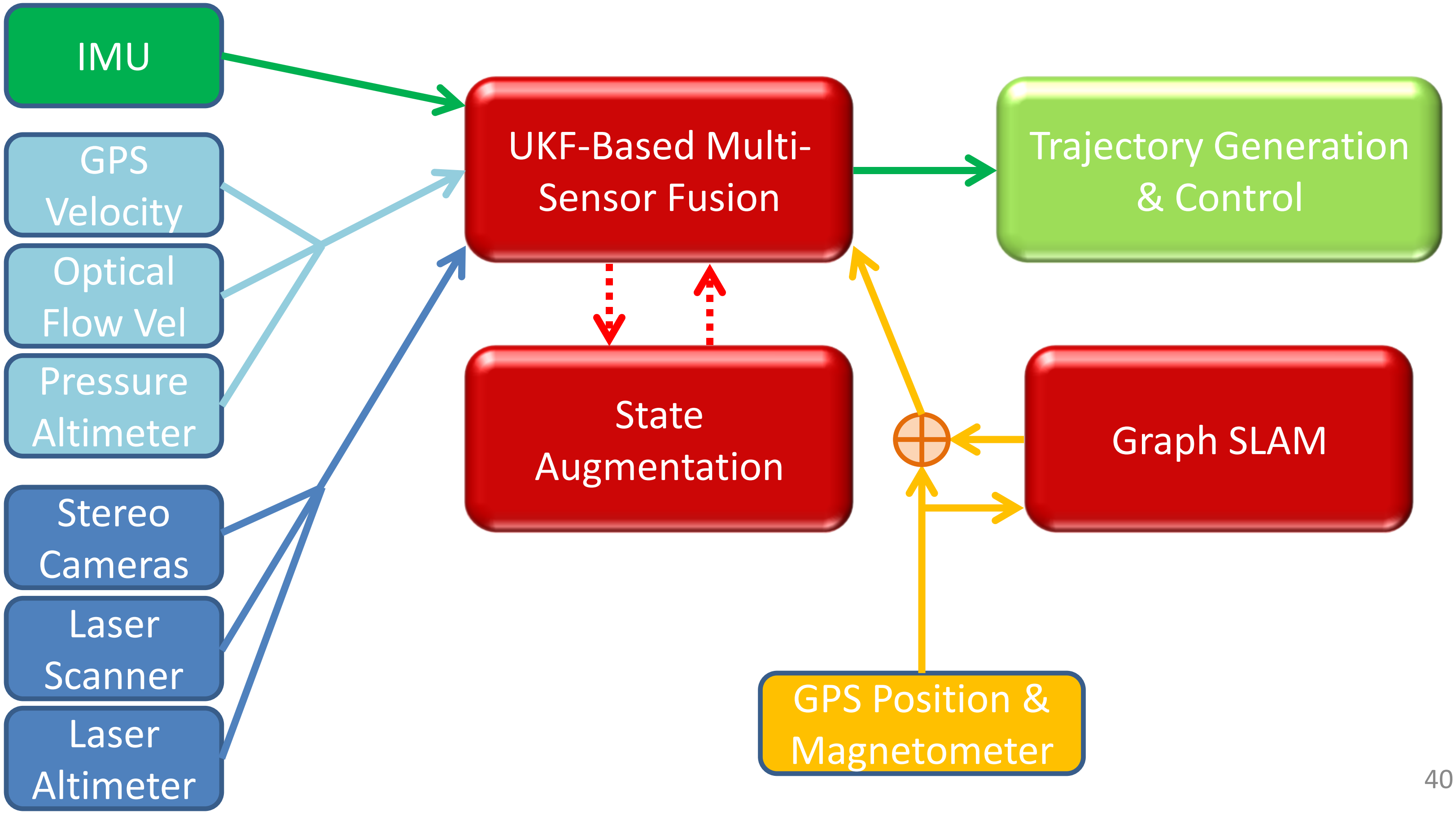


- Relative measurements
  - Laser scan matching – 3DOF Pose
  - Visual odometry – 6DOF Pose
  - Laser altimeter
  - $\mathbf{z}_t = h(\mathbf{x}_t, \mathbf{x}_{t-k}) + \mathbf{n}_t$



Robust Multi-Sensor Fusion for MAVs

- Add/remove heterogeneous sensors with minimum coding and calculation (no computation of Jacobian is required)



Sensors: IMU, Laser, Cameras, GPS
Autonomous Flight
All Processing Onboard
Length: 450 m, Speed: 1.5m/s

Robust State Estimation

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  - Initialize from an arbitrary unknown state
- Autonomy
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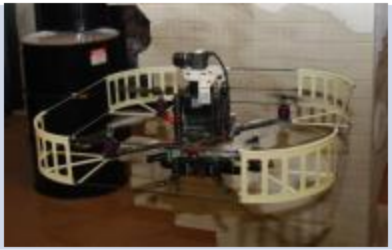	Laser IMU	Intel Atom 1.6GHz	1.7 kg	2.5D indoor	2010-2011
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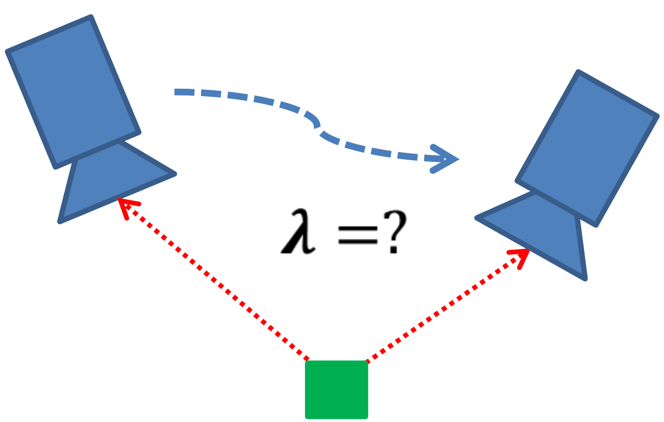
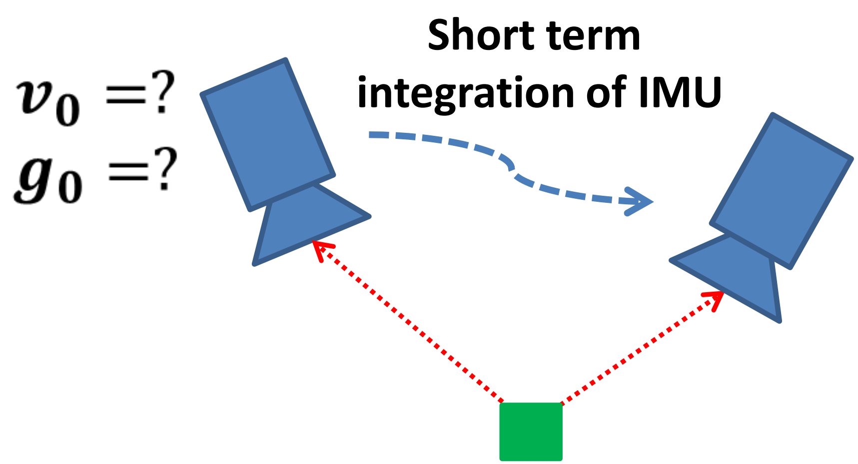
Monocular Visual-Inertial Estimation

Challenges – State Estimation

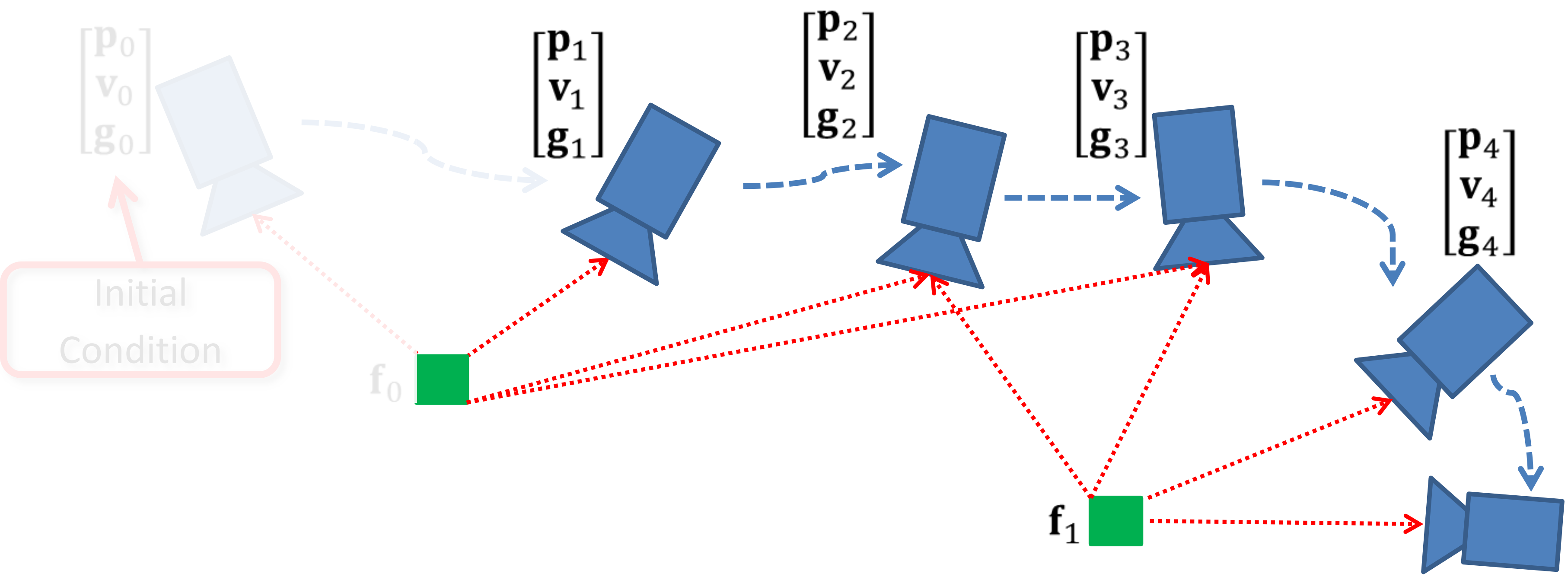
- Up-to-scale motion estimation and 3D reconstruction with monocular camera
- Add IMU, scale is (intuitively) observable, but…
  - Highly nonlinear system – requires good initialization
  - Initial condition – velocity and attitude (gravity), unknown
  - IMU noise is not modeled





Linear Sliding Window Monocular Visual-Inertial Estimator

- Over-constrained system for robustness against noise
- Our linear formulation enables recovery of initial condition
  - Optional nonlinear optimization to refine solution
- Marginalize old poses to bound computation cost



Linear Sliding Window Monocular Visual-Inertial Estimator

- Linear rotation estimation
  - Relative rotation constrains from gyroscope or epipolar geometry

$$\mathbf{R}^{B_0}_{B_0} = \mathbf{I}_3, \quad \mathbf{R}^{B_0}_{B_j} = \boxed{\hat{\mathbf{R}}^{B_i}_{B_j}}\mathbf{R}^{B_0}_{B_i}$$

Relative rotation

  - Rotation estimation by relaxing orthonormality constraints

$$\left[\mathbf{I}_3, \ -\hat{\mathbf{R}}^{B_i}_{B_j}\right]\boxed{\begin{bmatrix}\mathbf{r}^k_i \\ \mathbf{r}^k_j\end{bmatrix}} = 0 \quad k = 1, 2, 3$$

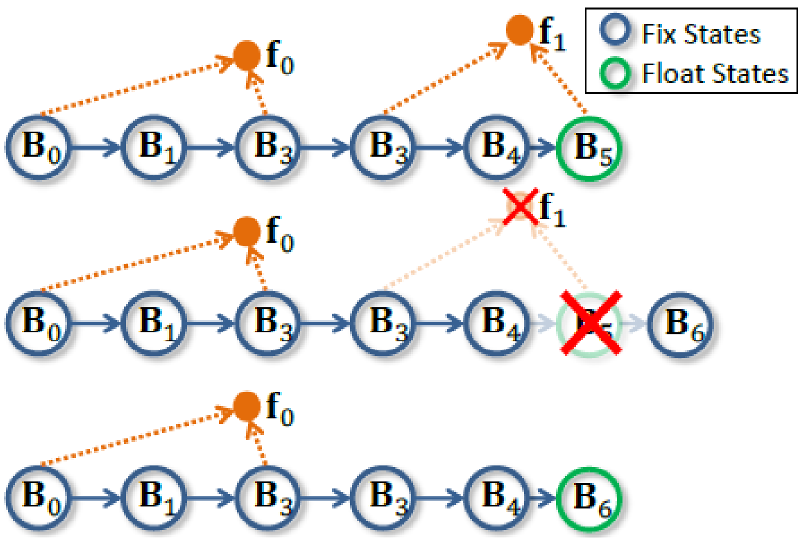
Columns of rotation matrices

- Linear system if first pose in the sliding window is used as reference frame
- Linear system -> Prior is not needed -> Initial condition recoverable

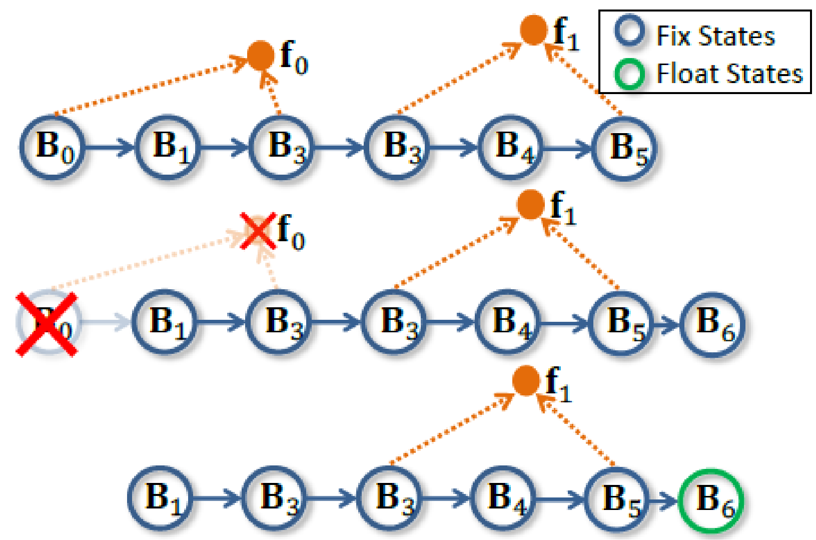
$$\min_{\mathcal{X}} \left\{ \underbrace{\cancel{(\mathbf{b}_p - \Lambda_p \mathcal{X})}}_{\text{Prior}} + \underbrace{\sum_{k \in \mathcal{D}} \left\| \hat{\mathbf{z}}^{B_k}_{B_{k+1}} - \mathbf{H}^{B_k}_{B_{k+1}} \mathcal{X} \right\|^2_{\mathbf{P}^{B_k}_{B_{k+1}}}}_{\text{IMU Constraints}} + \underbrace{\sum_{(l,j) \in \mathcal{C}} \left\| \hat{\mathbf{z}}^{B_j}_l - \mathbf{H}^{B_j}_l \mathcal{X} \right\|^2_{\mathbf{P}^{B_j}_l}}_{\text{Camera Constraints}} \right\}$$

Preserving Scale Observability During Degenerate Motion

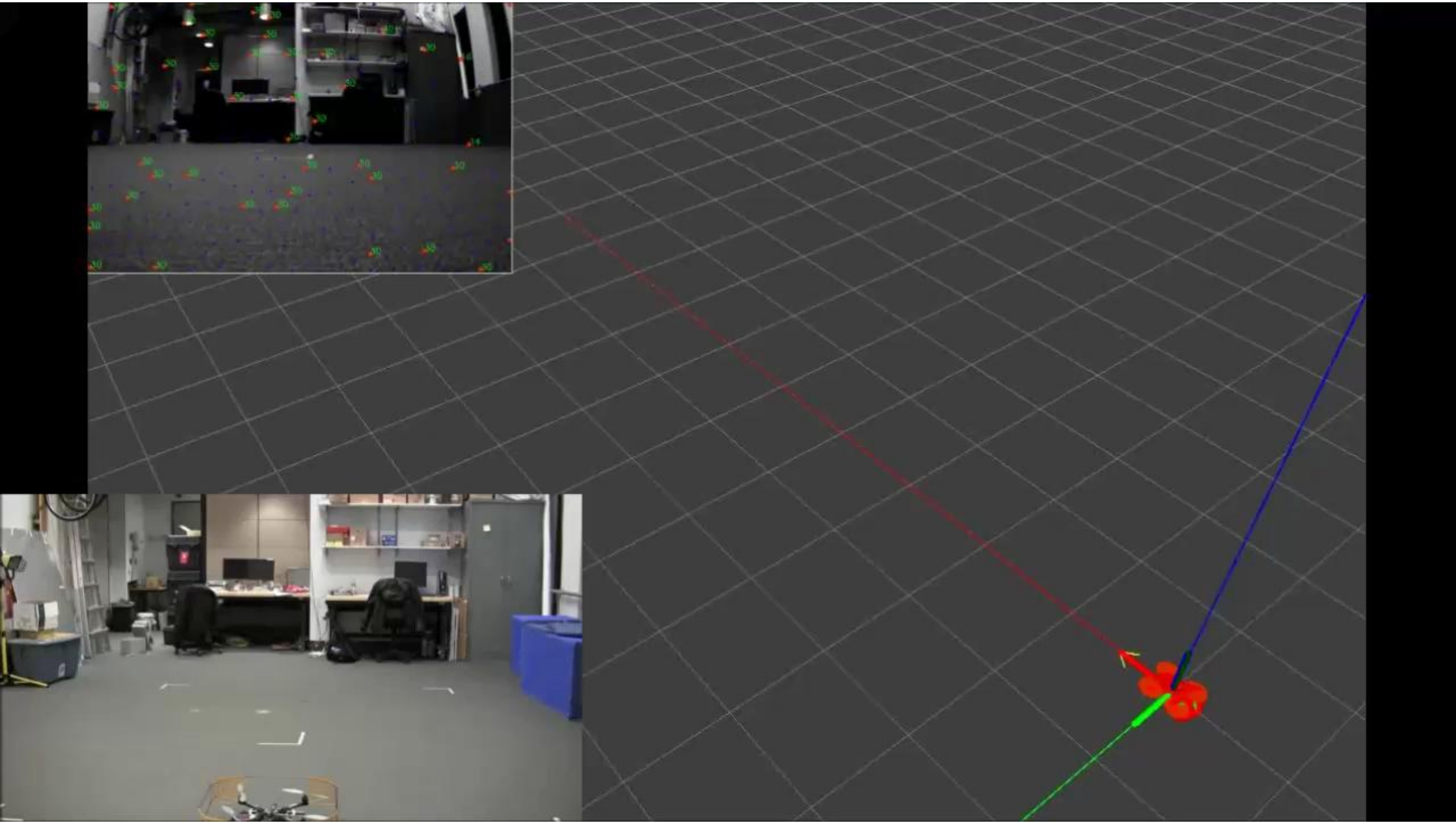
- General motion:
  - Linear acceleration is required to preserve scale observability
- Zero acceleration motion:
  - Preserve scale information via two-way marginalization



Newest: Keep acceleration measurements in the window



Oldest: Convert information from removed states into single Gaussian



Initialization-Free Monocular Visual Inertial State Estimation with Application to Autonomous MAVs
International Symposium on Experimental Robotics (ISER) 2014, To Appear

Summary on Estimation for MAVs

- Autonomous navigation in complex indoor and outdoor environments with micro aerial vehicles using a variety of sensors
- Robust state estimation
  - Power-on-and-go
  - Autonomy
  - Fault-tolerant
  - Fail-safe
- Fully integrated systems with onboard processing

Conclusion and Future Work

- Summary
  - Control and planning for aerial manipulation with motion capture systems
  - Vision-based servoing with proven stability
  - State estimation for autonomous flight
- Future Work
  - Merge all results together for robust autonomous aerial manipulation in challenging environments